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Design recommendations for solar organic Rankine cycle (ORC)–powered reverse osmosis (RO) desalination

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ABSTRACT

This paper deals with the design recommendations for solar reverse osmosis (RO) desalination based on solar organic Rankine cycles (SORC). This technology can be the most energy-efficient technology for seawater and brackish water desalination within the small to medium power output range (up to 500 kW) of the power cycle if the system is properly designed. However, theoretical studies, design proposals and experimental works are very scarce and only very few solar reverse osmosis systems driven by ORC has been either implemented or analysed in the past. In this paper, those systems are outlined and general design recommendations from previous detailed analysis already publish are given for future RO desalination system to be designed based on SORC. Useful information is given about the selection of the working fluid and boundary conditions of the ORC, operation temperature and configuration of the solar field, suited solar collector and thermal energy storage technology, etc. Recommendations are exemplified with well selected numerical cases based on recommended working fluids and solar cycle configuration with proper values of design point parameters. Recommendations given in this paper could be helpful in future initiatives regarding the research and development of this promising solar desalination technology.

Contents

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1. Introduction

Scarcity of safe energy and water resources is a vital problem for millions of inhabitants of the planet. This situation limits and delays the socioeconomic development of the communities where they live most of them being small villages. According to International Energy Agency data, in the MENA region (Middle East and North Africa) there were 23.3 millions people without electricity access in the year 2009 and this value came to 585.2 millions people in the case of sub-Saharan Africa [1]. For these areas of the world, data from World Health Organization say that rural population not served with improved drinking water sources came to 41 millions people in the MENA region and 278 millions people in the sub-Saharan Africa in the year 2008 [2]. Next to this scarcity is the worry about the global warming and its effects, not only in areas with energy and water scarcity as the aforementioned, but also in areas where these supplies are guaranteed. Solar energy, water desalination and the combination of both (solar desalination) can provide technological solutions to these problems. Solar energy can be used directly or indirectly for seawater and brackish water desalination with several technologies [3]. One of these technologies combines solar thermal energy production, the organic Rankine cycle (ORC) technology and the reverse osmosis (RO) desalination process. This combination was already studied at the end of seventies and beginning of the eighties of the last century for brackish water desalination due to the high oil prices as a result of 1970s energy crisis. Interest in this solar desalination technology aroused in the last years of twentieth century and at the beginning of 21st when several research and development initiatives were carried out. In a solar thermal driven-ORC–RO desalination system, solar energy gathered by a solar field is partially converted into thermal energy. This thermal energy is the input energy of the ORC-based power conversion unit whose mechanical energy output is consumed by the seawater or brackish water RO desalination process. Thermal energy rejected by the ORC at low temperature could be used for the preheating of the RO feedwater or other applications as seawater distillation or space heating. This paper focuses on general design recommendations for this technology derived from the global analysis performed and already published by the authors in several papers in which specific design aspects were thoroughly analysed [4–13].

This work has been partially carried out within the framework of the project entitled POWERSOL (Mechanical Power Generation Based on Solar Heat Engines). This project is supported in part by the European Commission under the Specific programme for research, technological development and demonstration: “Integrating and strengthening the European Research Area” (specific measures in support of INternational CO-operation, INCO). The main project objective is the development of an environmentally friendly reduced cost technology for shaft power generation, based on solar thermal energy, and optimized for supplying basic needs of rural or small communities. The project focuses on the technological development of a solar thermal-driven mechanical power generation based on a solar ORC with a power output between 100 kW and 500 kW and working temperature below 250 °C (POWERSOL system). Reverse osmosis desalination to cover the fresh water supply of said rural communities could be one of the suitable processes to be driven by the power unit. Design recommendations suggested in this paper are valid for small to medium capacity systems based on solar-thermal mechanical power generation. Therefore, these are also valid for POWERSOL technology. Main application for which these type of systems have been developed is water pumping for irrigation purposes. Comprehensive information about this application can be found in [4]. Other applications as electricity generation could have features applicable to solar thermal-driven RO. Experiences as the Coolidge Solar Irrigation Project [14], the Small Communities Project [15] and the system described by Schmidt et al. [16] are good examples of solar ORC applications. Other similar experiences are quoted by Curran [17]. In the case of RO desalination application, conclusions of review works performed by the authors [5] and most recently also by Ghermandi and Messalem [18] can be summarised as follows: theoretical studies, design proposals and experimental works are very scarce. In addition, such designs have not been optimized at all yet as will be shown. Therefore, this technology still exhibits a high potential of improving designs and the recommendations given in this paper could be helpful in future initiatives regarding the research and development of this promising solar desalination technology.

2. Solar thermal driven reverse osmosis: technology assessment

2.1. Technology development

This section presents a record of designs and pilot plants of solar thermal-driven RO systems existing so far leaving out the proposals already published by the authors. It is aimed to give an overview of the technological development of solar thermal-driven RO desalination including not only ORC-based systems but also dish-Stirling and hybrid systems. Pre-existing systems and designs proposals are grouped taking the solar thermal technology used into account and are given in order of overall efficiency values, starting from solar pond driven systems and ending by solar dish-Stirling driven systems. According to this criterion seven different designs arisen.

Design 1: Salinity-gradient solar ponds for driving an ORC/RO system. Two test facilities based on coupling salinity-gradient solar ponds with RO units were installed in El Paso (Texas, E.E.U.U.) and Los Baños (California, E.E.U.U.) [3]. In this type of design, the overall efficiency of the solar pond-driven ORC would be about 1.5%, assuming a thermal performance of the solar pond of 15% and a performance of the ORC coupled to it about 10% [19].

Design 2: Flat plate collector for driving an ORC/RO system. A first prototype of this design with a SOFRETES 2.5 kW-output solar heat engine with R114 as working fluid of the ORC and Gilotherm ADX 10 as heat transfer fluid was running in Cadarache (France) in 1978. This prototype was coupled to a 2.5 m^3/h brackish water RO unit with Pelton turbine as energy recovery device. For a feed water at 2 g/l and 50% of conversion the specific energy consumption claimed was 0.67 kWh/m^3 [20]. A second prototype with a larger SOFRETES unit (10 kW) with R11 as working fluid of the ORC and a 9 m^3/h brackish water RO unit was installed in El-Hamrawin (Egypt) in 1981. For a feed water at 3 g/l the specific energy consumption of the RO unit was 1.0 kWh/m^3 [21]. When these pilot plants were erected, typical state of the art values of the specific energy consumption of the RO process were about 8 and 12 kWh/m^3 for seawater with and without brine energy recovery respectively [21].

Design 3. Evacuated tube collectors for driving an ORC/RO system. The only experimental system currently existing under the knowledge of the authors has been erected to the North-East from Athens, Greece. In the framework of the RO-SOLAR-RANKINE project, the development, application, testing and performance evaluation of an autonomous low temperature solar organic Rankine cycle system for RO desalination was carried out. Experimental studies about solar ORC with HFC-134a as working fluid heated by evacuated tube solar collectors were conducted. Mechanical energy delivered by the ORC unit was directly used for driving the high pressure pump of a small reverse osmosis desalination unit, the feed pump of the ORC, the cooling water pump and the circulating pump. In the first design proposal, the solar ORC was driven with

top temperature about 77 °C by a solar field composed of direct flow evacuated solar collectors. Then, the overall performance of the Rankine cycle should be lower than 7% [22]. Experimental results about performance of this design under real solar conditions coupled to a RO unit of 0.3 m^3/h fresh water production capacity have been already published [23]. Main conclusion is the low value of the solar ORC efficiency (1.5%) because low values of the expander efficiency. The reported specific energy consumption of the RO process is about 2.3 kWh/m^3. In a second phase of the investigation into this design, a double cascade ORC with R245fa and R134a as working fluid of the upper and lower cycle respectively has been proposed [24,25]. Nominal average temperature operation of the solar field would be about 135 °C and the same vacuum tube solar collectors than in the first design would be used. Scroll expanders are proposed as mechanical production devices for the bottom cycle as well as the upper cycle. Kosmadakis et al. propose the double cascade for this new temperature level instead of the simple cycle because in the latter case the efficiency of the scroll expander would be too low due to the high value of the pressure ratio [25].

Design 4. Parabolic trough collectors (PTC) for driving a steam power cycle or ORC/RO system. Bowman et al. [26] propose a design that uses parabolic trough collectors for driving a 3.1 m^3/h brackish water reverse osmosis unit with fossil fuel backup and solar thermal energy storage. The solar field would be operated with a secondary working fluid. Mechanical energy is produced with two reciprocating steam engines. One of them is direct-connected to the high pressure RO pump and the other one is used to produce electrical power for auxiliary consumption. Besides that, there is a patent of this design [27]. Recently, Karellas et al. [28] have proposed a design of an autonomous hybrid solar thermal ORC–photovoltaic (PV) driven reverse osmosis desalination system. PV system with a battery array is used for satisfy the power demand of the auxiliary equipment and there is no solar thermal energy storage. R134a is proposed as working fluid of the 250 kW solar ORC and a thermal oil is used as heat transfer fluid of the solar PTC field.

Design 5. VARI-RO technology for driving an RO system. An integrated pumping and energy recovery system for reverse osmosis called VARI-RO was designed and constructed in the nineties in E.E.U.U. Childs et al. [29] proposed that this technology could be coupled to solar Dish-Stirling systems with global efficiencies between 22% and 25% and parabolic trough collectors with efficiencies about 20%. Nevertheless, none of the proposals have been implemented already to the knowledge of the authors and no new information about this technology has been published to date.

Design 6. Dish-Stirling collectors for driving a RO system. The proposal of El-Nashar and Husseiny [30] of a high temperature (Dish Stirling) solar heat engine for driving a brackish water RO unit has interesting prospects because of the higher top temperature compared to parabolic troughs, which results in higher performance. The proposal includes fossil fuel backup and solar thermal energy storage. Estimates of typical BWRO specific energy consumption are between 1.66 and 1.45 kWh/m^3 using recovery turbine/generator for recovery ratios between 60% and 90%. Without energy recovery these values would be between 2.20 and 1.54 kWh/m^3 [30].

Design 7. Solar thermal RO/Photovoltaic driven electrodialysis (ED). Husseiny and Hamester [31] propose a design of a hybrid RO-ED commercial solar desalination plant of 6000 m^3/day. In the design, the hybrid plant was composed by a solar thermal-driven reverse osmosis system besides a solar photovoltaic powered electrodialysis system.

2.2. Technology assessment

This section is devoted to give a general assessment of the efficiency of solar ORC driven RO desalination. Performance of the technology should be depicted relating the solar energy gathered by the solar field and the amount of desalted water produced with the reverse osmosis desalination system. Therefore, quotient between solar energy reaching the aperture area of the solar field ($A_a \cdot G_a$) and volumetric flow rate of fresh water (q_P) is taken as the performance parameter of the solar desalination system in a given operation point. This quotient can be linked with representative parameters of the solar power cycle and the reverse osmosis unit. For the solar power cycle, its net efficiency (η) is chosen, defined as the quotient between the net mechanical power output delivered by the overall solar power cycle and the solar power reaching the aperture area of the solar field. This definition does not depend on the solar collector technology used in the solar field. In the case of the RO system, its specific energy consumption (W_{RO}) is chosen, defined as the total energy consumed by the desalination process to produce one unit of desalted water. Like in the solar power cycle efficiency, this definition does not depend on neither the feed water salinity nor the brine energy recuperation device used in the RO unit. According to the aforementioned definitions, the following expression gives useful assessment information if the values of η and W_{RO} are well defined:

$$\frac{A_a \cdot G_a}{q_P} = \left(\frac{W_{RO}}{\eta}\right) \tag{1}$$

From the analysis performed by the authors in previous work optimized design values of the solar organic Rankine cycle (ORC) efficiency driven with stationary solar collectors and parabolic trough collectors can be between 4% and 23% [6,7,12]. Lower values correspond to the low temperature solar ORC with standard and advanced flat plate collectors (4–6%) and evacuated tube collectors (~8%) and higher values corresponding to medium temperature solar ORC with parabolic trough collectors and fluids like toluene and benzene as working fluids of the regenerative ORC (20–23%). On the other hand, if a solar pond is used as solar energy collection system this value can be as low as 1.5% [19]. As regards current RO specific energy consumption values, if pressure exchangers are used as brine energy recuperation devices, values of W_{RO} are about 0.5 kWh/m^3 and 4.0 kWh/m^3, lower values corresponding to low salinity brackish water RO (BWRO) desalination and higher values corresponding to high salinity seawater RO (SWRO) desalination. With this information about solar power cycle performance, the aperture area needed per unit of volumetric flow rate of fresh water (A_a/q_P) as a function of the specific energy consumption of the RO desalination system is showed in Fig. 1 for a fixed value of the solar irradiance on the aperture area of the solar field of G_a = 1000 W/m^2. The scale of the *x*-axis has been extended up to 12 kWh/m^3 because this was the typical value of the specific energy consumption of SWRO without energy recovery in the year 1981 according to Libert and Maurel [21]. With this figure one can understand the main reason because solar thermal RO desalination is a promising solar desalination technology these days and why this technology was not developed in the past: the dramatically decreasing in the energy consumption of the reverse osmosis desalination. In fact, early solar thermal RO pilot plants were designed for brackish water probably because the lower specific energy consumption in comparison with seawater RO. As an example, consider the pilot plants based on SOFRETES units [21] coupled to SWRO desalination units. For a solar power cycle efficiency of 5% with a solar irradiance of 1000 W/m^2 on the aperture of the solar field and a specific energy consumption of the SWRO unit with energy recovery of 8 kWh/m^3, the aperture area needed to produce 1 m^3/h of desalted water would be about 160 m^2. However, assuming a current value of 3 kWh/m^3 for a SWRO unit with energy recovery the aperture area needed would be about 60 m^2. If we take into account that the cost of the solar field is the major cost of the solar power cycle, it is clear that the advance in

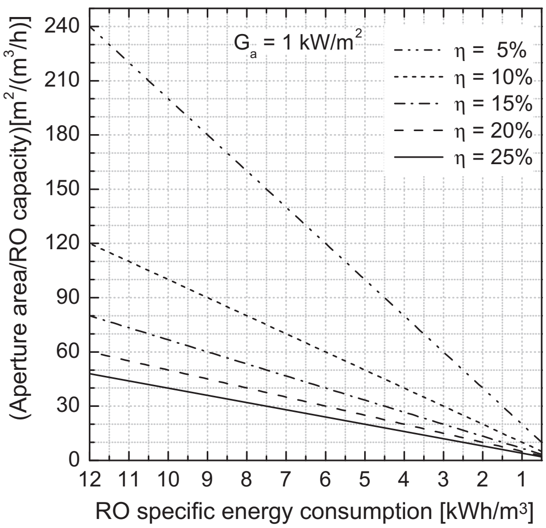

Fig. 1. Aperture area per unit of reverse osmosis fresh water capacity for a given value of the solar irradiance (1 kW/m^2) and different values of the solar power cycle efficiency (η).

RO technology has been crucial for the future development of said technology.

With more general purpose and current validity, contour plots of the quotient given by ec. 1 as a function of solar power cycle efficiency and RO specific energy consumption within the fixed intervals are shown in Figs. 2 and 3. Fig. 2 would be valid for systems which use solar ponds, stationary solar collectors (standard flat plate, compound parabolic concentrators, evacuated tube collectors) and even parabolic trough collectors without regeneration process and/or high condensation temperatures in the ORC. For this reason, solar power cycle efficiency values change from 1% up to 10%. Fig. 3 would be valid if single-axis tracking solar collectors were used in the solar field (linear Fresnel concentrators, parabolic trough collectors). These graphs allow us to do preliminary and comparative assessment of this technology, for example, with respect to solar distillation and photovoltaic powered (PV) RO

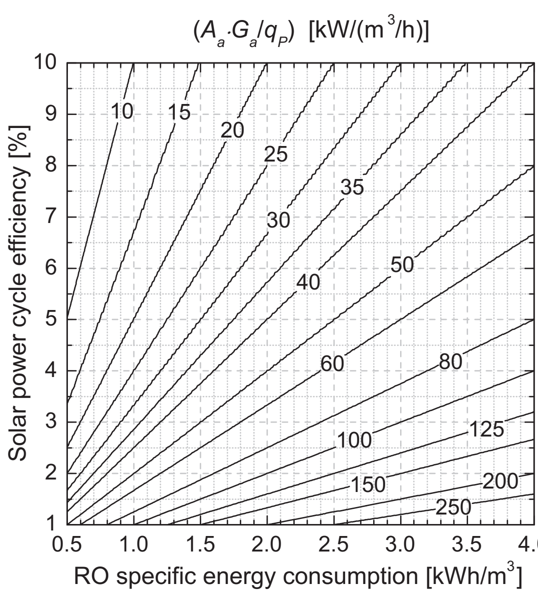

Fig. 2. Solar power needed on the aperture area of the solar field [kW] per unit of reverse osmosis capacity [m^3/h] as a function of the specific energy consumption of desalination process and the solar power cycle efficiency if the latter is between 1% and 10%.

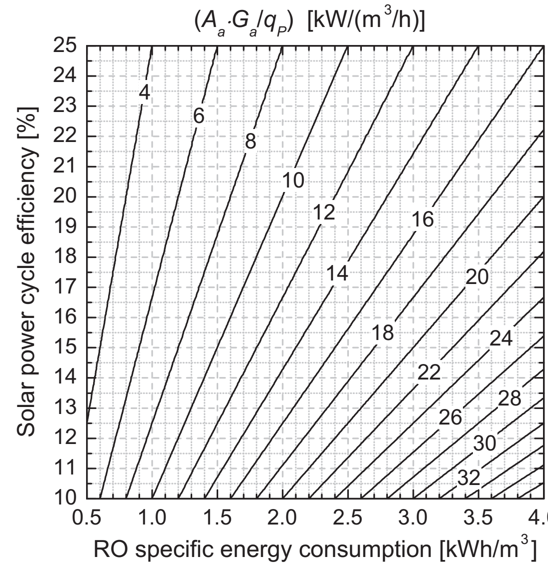

Fig. 3. Solar power needed on the aperture area of the solar field [kW] per unit of reverse osmosis capacity [m^3/h] as a function of the specific energy consumption of the desalination process and the solar power cycle efficiency if the latter is between 10% and 25%.

systems and also among different designs like already stated in the previous section. Performance estimate of the system can also be given whatever the design value of the solar irradiance is, corresponding to the value of 1 kW/m^2 the value of the quotient directly observed in the graphs. For example, if the estimate to be done is about a system with parabolic trough collectors a design value of the direct solar irradiance is needed. A typical value could be around 850 W/m^2 so in this case, the value directly read in Fig. 3 must be multiplied by (1/0.85) to obtain the aperture area per unit of RO capacity needed.

With respect to PV-RO, if a value of 11–13% is assumed as maximum current solar to electric conversion efficiency attainable with the photovoltaic field, this value could be exceeded according to Fig. 3 with solar ORC driven RO technology. In addition, unlike PV system, solar ORC does not produce only mechanical power: an important amount of heat is available at low temperature that could be used in another application. On the other hand, last experimental results about multi-effect solar distillation connected to an absorption heat pump [32,33] exhibit solar energy requirements similar to those obtained by solar ORC when the individual thermal performance of the Rankine cycle is about 7%.

3. Design recommendations

In this section, general design recommendations for solar thermal driven reverse osmosis desalination are given and explained. They are valid for low to medium size solar desalination systems with mechanical power output of the solar power cycle up to 500 kW, maximum top temperature up to 350 °C and stationary or single-axis tracking solar collectors as solar energy collection devices. The design analysed is based on Fig. 4. Thermal energy delivered by the solar field ($\dot{Q}_{ORC,in}$) is used for the high pressure heating process of an organic Rankine cycle (ORC). An internal heat exchanger can be used for the recuperation of thermal energy from the turbine outlet stream. Mechanical energy generated by the turbine is used for driving the RO unit. As it has been commented in the Introduction, POWERSOL technology must be and optimized technology for supplying basic needs to rural or small communities. This entails a series of design consequences as the proper mechanical output power interval of interest, which has been fixed in

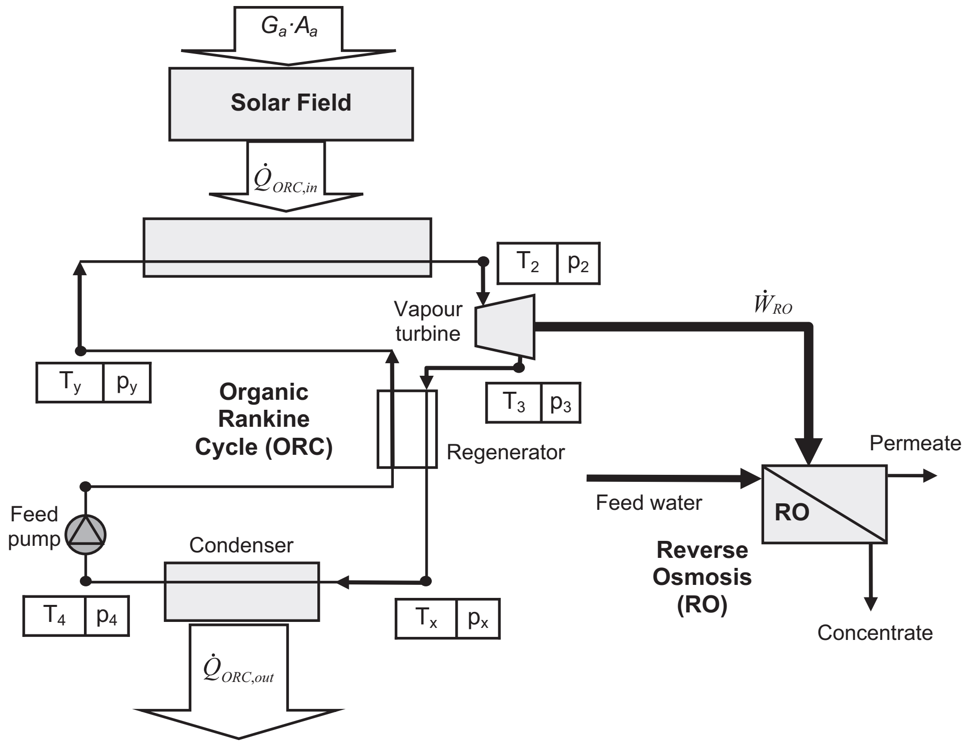

Fig. 4. Basic layout of the solar thermal organic Rankine cycle-powered reverse osmosis system.

100–500 kW. Therefore, design recommendations given in this section are also applicable to POWERSOL technology and the numeric examples that will be given will correspond to this case.

3.1. Selection of solar power cycle features

3.1.1. Selection of working substance of Rankine cycle

Organic Rankine cycle (ORC) is recommended as power conversion unit for mechanical power output values below 1 MW and top temperature values below 350 °C. In general, thermal efficiency of the simple Rankine cycle (saturated or superheated without recuperation) is almost proportional to the isentropic efficiency of the vapour turbine. For the mechanical power output levels below 1 MW, vapour turbine designs give higher values of the efficiency if a working fluid of higher molecular weight and lower isentropic enthalpy drop is used instead of water [15,34,35]. For this reason, ORC with a proper selected working fluid yields higher thermal efficiencies than the steam Rankine cycle in exploiting low or medium hot temperature sources with mechanical power generation purposes. Besides that, at these temperature levels, condensation of steam in the expansion process could be unacceptable which does not happen with a great number of organic substances due to their dry fluid behaviour. Many organic substances have these characteristics so they are and have been used for years in binary geothermal power plants. Finally, there are a great number of organic substances that could act as working fluid of the solar ORC. This fact allows to make the ORC operation fits the top and lowest temperatures of the cycle by selecting the working fluid. This is particularly interesting in the case of the solar thermal driven ORC because top temperature of the cycle depends on the solar collector technology used.

From the detailed working fluid analysis performed for medium temperature solar ORC it is concluded that maximum temperature attainable in the solar cycle could be limited not only by the solar collector technology used but also by the limited thermal stability and high toxicity of the working fluid. Toluene is one of the fluids already used in medium temperature solar ORCs and is a "classical fluid" aforementioned in several publications on this topic. With this fluid, high solar power cycle efficiencies can be obtained (for example, up to 23% [6]) but it has a high toxicity level. On the other hand, siloxanes can be an alternative for the medium temperature solar ORC because their better thermal stability and toxicity levels. Reasonable values of the solar cycle efficiency can be reached using the regeneration process in the subcritical ORC (for example, up to 19% by using siloxane MM [6]). In the case of the solar ORC with stationary solar collectors, since maximum temperatures in the cycle are lower the fluid-selection process is less complex because the set of proper substances is larger and the final selection will not be so conditioned by the thermal stability problem although this factor must be always considered. Fluids as isobutene, isopentane, R245ca and R245fa can be good options yielding values of the solar power cycle around 5% with flat plate collectors and 8% with evacuated tube solar collectors [12]. In the framework of the POWERSOL project, R245fa was the fluid initially selected for the solar ORC pilot plant erected in the Plataforma Solar de Almería. However, thermal stability of R245fa was not guaranteed for temperatures beyond 190 °C. For this reason, the current working fluid in the POWERSOL pilot plant is the Solkatherm® SES36, an azeotropic refrigerant mixture of 65 mass% R365mfc (1,1,1,3,3-pentafluorobutane) and 35 mass% perfluoropolyether.

3.1.2. Selection of the solar field configuration

In relation to the configuration of the solar field, two possibilities could be used, Direct Vapour Generation (DVG) configuration, in which the working fluid of the ORC is heated inside absorber tubes of the solar collector, or use of synthetic oils as Heat Transfer Fluid (HTF).

The DVG configurations imply higher values of the solar power cycle efficiency compared to the HTF configuration for a fixed value of the solar field outlet temperature. In addition, investment cost per kilowatt of installed mechanical power would be lower too. However, although the technical feasibility of the direct steam

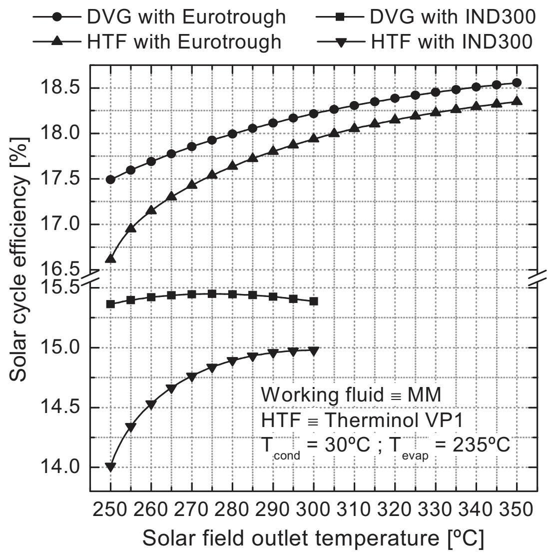

Fig. 5. Solar cycle efficiency dependence on solar cycle configuration and solar field outlet temperature with IND300 (DVG: ■, HTF: ▼) and Eurotrough (DVG: ●, HTF: ▲) parabolic trough collectors. Working fluid, condensation and evaporation temperature of the regenerative ORC are MM, 30 °C and 235 °C respectively.

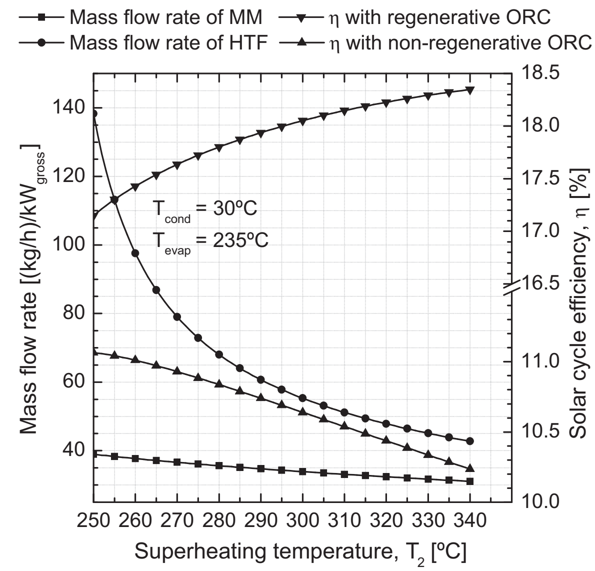

Fig. 6. Solar cycle efficiency with non-regenerative (▲) and regenerative ORC (▼) and mass flow rate of MM (■) and Therminol VP1 (●) per unit of gross mechanical power output as a function of final superheating temperature in the ORC. A value for the regenerator effectiveness of 80% was chosen for the regenerative case. All the results were obtained with PTC Eurotrough.

generation (DSG) with parabolic trough collectors has been already demonstrated [36], this is not the case of DVG with organic fluids. No references about DVG of organic substances in parabolic troughs exist from the knowledge of the authors. Therefore, data of experimental evaluation of the transverse temperature gradients within the walls of the absorber of the solar collector are not available. These data are especially important in the two phase flow region in order to determine the technical suitability of DVG for solar ORC.

Besides that, the general comparison of solar ORC performance for DVG and HTF technologies should be considered. The differences between the solar power cycle efficiency with both configurations decrease as the maximum temperature of the cycle increases [7]. Fig. 5 shows the influence of the top temperature (solar field outlet temperature) on the thermal performance of the solar ORC for a general comparison between DVG and HTF configurations. Two parabolic troughs, IND300 and Eurotrough, are used for driving an ORC (regenerator effectiveness, $\varepsilon_{reg} = 0.8$, turbine and pump performance, $\eta_t = \eta_b = 0.75$) operated with hexamethyldisiloxane (MM) ($T_{evap} = 235\,^{\circ}$C; $T_{cond} = 30\,^{\circ}$C), at a given design point direct solar irradiance ($G_b = 850\,\mathrm{W/m^2}$).

A rather flat behaviour of the thermal performance is shown by the DVG configuration for a wide range of top temperature. On the other hand, the influence of the top temperature for the HTF configuration is significantly higher. Since the two parabolic troughs analysed are quite different, similar results would be obtained by using different collectors. Therefore, a general recommendation is to analyse the dependence on the top temperature of the solar ORC performance for a given collector. Based on this analysis, the most mature technology based on HTF is recommended with an adequate selection of the top temperature, in order to achieve similar performance of DVG configuration.

3.1.3. Selection of solar ORC features

Since the fluid used in the ORC is recommended to have dry-fluid behaviour, a priori is not necessary a stage of superheating in the cycle in order to avoid condensation problems in the steam turbine. In order to increase the efficiency of the cycle the incorporation of an internal heat exchanger or regenerator in the ORC is recommended as first choice. The higher the top temperature of the solar cycle, the stronger this recommendation because the higher the heat-recuperation potential. However, the analysis of their effect on performance of the solar cycle is advised in each case since this modification in the ORC requires a greater operating temperature of the solar field.

It has been found that the vapour superheating in the non-regenerative ORC can result in a reduction of cycle thermal efficiency. The importance of this reduction depends on the working fluid, operating conditions of the cycle and efficiency curve of the solar collector. Since the incorporation of a stage of superheating in the ORC yields higher average operating temperatures of the solar field, superheating in the non-regenerative solar ORC is not recommended. On the contrary, superheating combined with the regeneration process may result in increased performance of the solar cycle, being the effect of superheating in this case relatively smaller than the regeneration effect itself generally.

For a fixed value of the mechanical power output, working fluid mass flow rate depends on the superheating temperature. These behaviours are exemplified in Fig. 6 where solar cycle efficiency (η) and mass flow rate of ORC's working fluid and heat transfer fluid per unit of gross mechanical power output of the cycle are shown as a function of the final superheating temperature. These results were obtained for a solar power cycle with Therminol VP1 as heat transfer fluid and hexamethyldisiloxane (MM) as working fluid of the ORC. Solar collector considered was the Eurotrough parabolic trough collector with efficiency curve parameters given in [37]. Dependence of the mass flow rate with final superheating temperature could be used for the adjustment of the mass flow rate of the working fluid of the solar field, especially if its efficiency is weak dependent on the value of ORCs superheating temperature. This technique could also be used in the DVG configuration where same behaviour is also found and where thermo-hydraulic conditions of the flow inside the absorber tubes can play an important role.

3.1.4. Selection of maximum temperature and the solar collector technology

In general, the higher the maximum temperature of the regenerative organic Rankine cycle, the higher its thermal efficiency. This implies a higher operation temperature of the solar field and

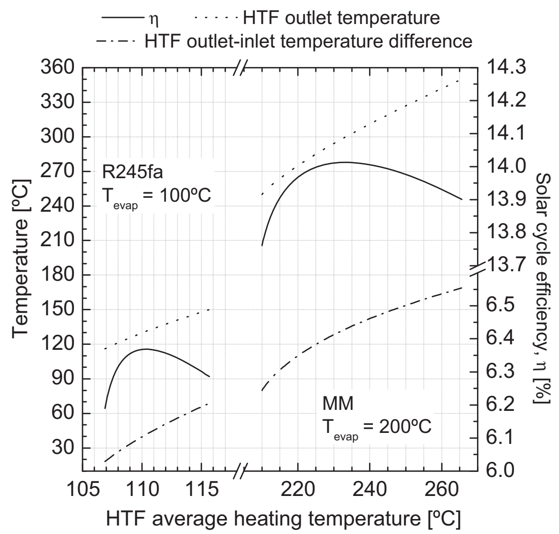

Fig. 7. Solar cycle efficiency, outlet temperature and inlet–outlet temperature difference of the heat transfer fluid as a function of the average heating temperature in the solar collector. Condensation temperature of 30 °C, and isentropic turbine efficiency of 75% were fixed in both cases.

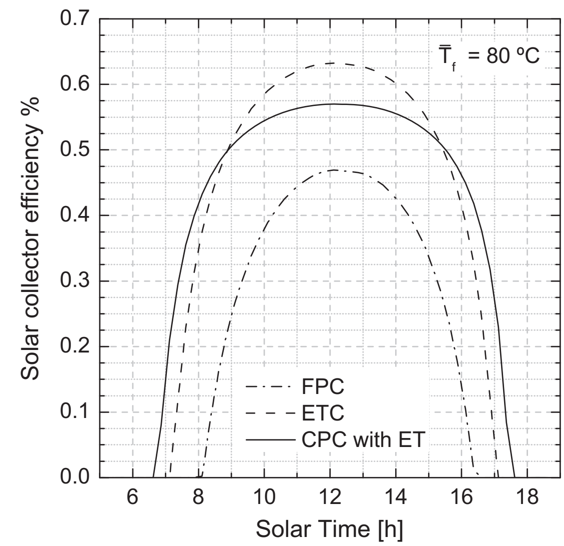

Fig. 8. Instantaneous solar collector efficiency, for a mean operation temperature of 80 °C, as a function of solar time for standard flat plate collector (FPC), evacuated tube collector (ETC) and compound parabolic concentrator with evacuated tubes (CPC with ET).

hence its efficiency would be lower. Therefore, the design value of the operation temperature of the solar field must be optimized. Depending on the solar collector model, working fluid of the ORC and operating conditions of the solar cycle (especially those relating to regeneration process), increasing the average heating temperature in the solar collector can make increase, decrease or reach a maximum the efficiency of the solar power cycle. For the latter case, example in Fig. 7 is given for two different temperature levels of the solar ORC in a HTF configuration with R245fa and MM as working fluids with stationary and single-axis tracking solar collectors respectively. Water and synthetic thermal oil (Therminol VP1) were used as heat transfer fluids of the low and medium temperature cycles respectively and condensation temperature of 30 °C was fixed for both. Analysis of the effect of the average heating temperature of the HTF in the solar field is especially interesting in this configuration because the difference between outlet and inlet temperatures could be conditioned by the thermal energy storage. That fact can be exemplified with the medium temperature case of Fig. 7. According to the results shown in said graph, solar cycle efficiency reaches the maximum if average heating temperature around 230 °C is fixed. This value corresponds to an inlet–outlet temperature difference about 140 °C. If, for example, sensible thermal energy storage in a stratified tank would be used this temperature difference could be excessive. If the optimal temperature difference to get the stratification in the tank would be 70 K then the average heating temperature in the solar field should be 210 °C, which does not yield the highest solar cycle efficiency. However, influence of average heating temperature could have a weak effect around the maximum of the solar cycle efficiency as happens in Fig. 7.

In any case, depending on the desired value of the solar cycle efficiency, parabolic trough collectors (PTC) and linear Fresnel concentrators are recommended for top temperatures up to 350 °C, evacuated tube collectors (ETC) and compound parabolic concentrators with evacuated receivers or with a second stage concentrator are recommended for top temperature cycles between 100 °C and 150 °C. Finally, if top temperatures below 100 °C are required, flat plate collectors (FPC) could be used. However, in this case, thermal energy output of the solar field with FPC should be evaluated in comparison with ETC because the difference in dependence of the solar collector efficiency on the solar irradiance and incidence angle. This difference is shown in Fig. 8 where daily instantaneous efficiency of three different types of solar collectors (flat plate collector (FPC), evacuated tube collector (ETC) and compound parabolic collector with evacuated tubes (CPC with ET)) is represented for a typical day of June.

3.1.5. Selection of minimum temperature

Condensation temperature of the organic Rankine cycle (ORC) is the minimum temperature of the solar ORC and its efficiency is strong dependent on the value of this temperature as can be observed in Figs. 9 and 10. In these figures, optimized values of η are given as a function of the condensation temperature for six representative examples: non-regenerative and regenerative low temperature solar ORC cycles with R245fa as working fluid of the ORC with compound parabolic collector (model AoSol 1.12X)

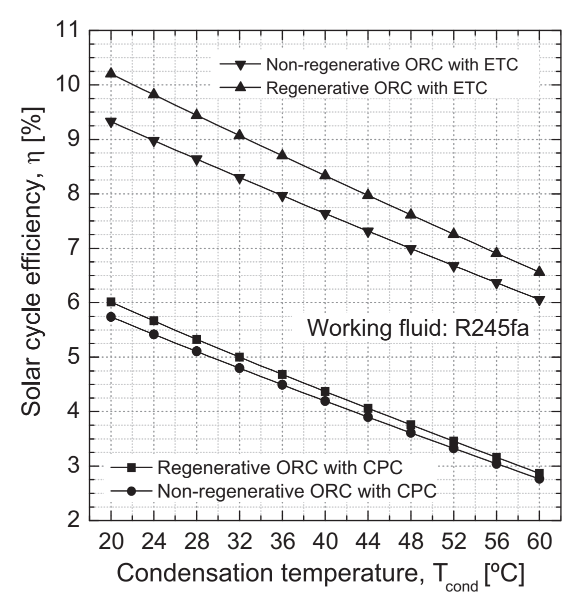

Fig. 9. Solar power cycle efficiency as a function of condensation temperature of the organic Rankine cycle (regenerative and non-regenerative) with R245fa as working fluid and stationary solar collectors.

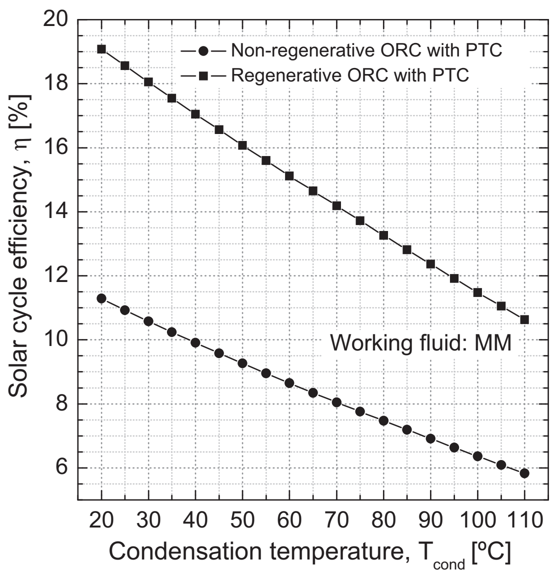

Fig. 10. Solar power cycle efficiency as a function of condensation temperature of the organic Rankine cycle (regenerative and non-regenerative) with MM as working fluid and parabolic trough solar collector.

and evacuated tube collector (model VITOSOL 300) (Fig. 9) and non-regenerative and regenerative medium temperature solar ORC cycles with MM as working fluid of the ORC and parabolic trough collector (model Eurotrough) (Fig. 10). Therefore, in order to maximize the solar power cycle efficiency, operation of the ORC at the lowest condensation temperature attainable is recommended. However, lower limit of the condensation temperature is affected by:

- Condensation pressure, which is also working fluid-dependent. Very low condensation pressures can yield high specific volume of the vapour to be cooled in the regenerator and the condenser and considerable vacuum level may be needed.
- Thermal heat capacity and temperature of the refrigerant medium available to be used, which can depend on the season and the location of the system.
- Regenerator and condenser cost, directly related to the required heat exchanger area.

To sum up, the recommended condensation temperature is the lowest possible one compatible with the condensation pressure, temperature and heat capacity of the cooling medium and cost of heat exchangers. The lower the top temperature of the solar cycle, the stronger this recommendation.

In Figs. 9 and 10 two other characteristics of the solar ORC can be observed. Firstly, greater effect of condensation temperature in the regenerative cycle than in the non-regenerative one. Secondly the higher the top temperature cycle, the higher the importance of the regeneration process. The latter has been already mentioned.

3.1.6. Selection of cooling system for heat rejection

One of the main differences between solar ORC and a photovoltaic system is the huge amount of heat rejected by the ORC at low temperatures that could be used in another process. Use of this thermal energy as heat input in water desalination is discussed in this section.

In the case of distillation process, a condensation temperature increase would be needed for using the waste heat for driving the distillation unit. Membrane distillation process, multi-effect distillation (MED) or multi-stage flash (MSF) distillation could be used, thus resulting in a hybrid solar desalination system (RO/distillation). The authors analysed such hybrid systems [10] and obtained in hybrid systems higher solar energy requirements for the unitary fresh water production than in the single solar RO system. Therefore, cooling of the solar ORC with the feed water stream of a distillation unit is not recommended because of the strong dependence of the solar power cycle efficiency on the condensation temperature of the ORC and the low specific energy consumption of the reverse osmosis system.

Another possibility for exploiting the thermal energy rejected by the solar ORC for desalination purposes is the heating of the RO feed water. The increasing in the fresh water productivity of a RO membrane element when the feed water temperature increases is about 3% per Kelvin. However, when 6 or 7 membrane elements are connected in series inside a pressure vessel the final increasing in the productivity is lower. In fact, the temperature rise of feed water found in the medium temperature system does not imply a significant increase in the fresh water production [8]. The smaller the cycle efficiency and the higher the specific energy consumption of reverse osmosis unit the higher this increase. Therefore, cooling of the ORC with the RO feed water with the objective of increasing the productivity of the RO system is not recommended although it may be an option as the cooling medium itself. It is recommended to evaluate the cost of operating and maintaining the condenser and possible pump needed to circulate the feed water as coolant.

Finally, with regard to water or air-cooling of the condenser of the solar power cycle, liquid cooling is recommended as preferential option since in a solar desalination system there are liquid streams available by default (feed water, concentrate and permeate).

3.2. Selection of RO subsystem design

Obviously, the lower the specific energy consumption of the reverse osmosis, the better the efficiency of the solar thermal driven desalination system. Fig. 1 shows the significant effect of the specific energy consumption of the RO process on the aperture area of the solar field.

The reduction of specific consumption of a reverse osmosis unit is determined by the permeability of the membrane, the energy recovery system used and also by its size because the design value of the conversion can depend on the number of membranes connected in series in each pressure vessel. In any case, the RO specific energy consumption will always be minimised if high permeability membranes and pressure exchangers as energy recovery devices are used. Therefore, its use is recommended for this technology to reduce the aperture area of the solar field and the size of the ORC unit.

A careful selection of the energy recovery device and the pressure vessel design is required to minimise the specific energy consumption. The main energy consumption should be about 2 kWh/m^3 in an optimized design. Different membrane models of the same brand should be used in order to optimize the pressure vessel design. Previous analysis could be useful in the design of the RO subsystem [8,38].

3.3. Selection of the connection of the ORC to the RO subsystem

Theoretically, the connection of the power cycle to reverse osmosis system could be carried out in three different ways:

- Direct mechanical coupling: all the mechanical power produced by the vapour turbine is transmitted to the pumps for reverse osmosis system directly.

Table 1
Evaporation temperature, final superheating temperature and thermal efficiency of the ORC, inlet–outlet heat transfer fluid temperatures and gross efficiency of the solar cycle with R245fa as working fluid.

	With sensible TES	With PCM TES
"Cycle 2" with water as HTF and G_a = 1000 W/m^2		
T_{evap} [°C]/T_2 [°C]	120/145	98/98
η_{ORC} [%]	16.83	13.34
T_{OUT}/T_{IN} [°C]	150/108	150/108
PCM melting point [°C]	–	103
η_{gross} [%]	8.8	6.9
"Cycle 3" with Santotherm 55 as HTF and G_a = 850 W/m^2		
T_{evap} [°C]/T_2 [°C]	145/220	145/173
η_{ORC} [%]	21.22	19.08
T_{OUT}/T_{IN} [°C]	230/193	230/193
PCM melting point [°C]	–	183
η_{gross} [%]	16.1	14.6

- Electrical coupling: all the mechanical power produced by the vapour turbine is converted into electrical power which is distributed to all points of consumption of desalination system.
- Mechanical and electrical coupling. Part of the mechanical power produced by the vapour turbine is directly consumed by the high-pressure pump. The rest of the mechanical power produced is converted into electricity which is then distributed to points of consumption where it is necessary.

Direct mechanical coupling involves no need for electric motors for hydraulic pumps. However, mechanical systems needed to transfer the necessary mechanical power to devices other than the high pressure pump as would be the circulation pump would have to be designed. A coupling of this type is characteristic of the system of Manolakos et al. [23] and the direct drive engine configuration of the VARI-RO technology [29]. On the other hand, electrical coupling raises the possibility of supplying all the points of consumption in the reverse osmosis plant directly after processing of the mechanical power produced by the turbine. As drawback, each pump of the system would need its own electric motor. Finally, the mechanical and electrical coupling could be the most interesting. Since the principal energy consumer device of the reverse osmosis system is the high-pressure pump, the shaft of the vapour turbine could be directly connected to the high pressure and an electric generator. The latter produce the amount of electricity needed in all consumption points different to the high pressure pump. It might also be interesting the direct mechanical coupling between turbine and the high-pressure pump so that the energy required in the other points of consumption in the reverse osmosis plant was produced by photovoltaic panels.

3.4. Selection of the thermal energy storage

Use of thermal energy storage in the solar thermal driven RO desalination systems would increase the solar fraction or availability if fossil fuel backup is or is not used respectively. Design recommendations given in this section are only restricted to what kind of thermal energy storage would be the most appropriate taking into account its effect on the top temperature of the ORC. In a HTF configuration of the solar ORC, if a latent heat thermal energy storage system would be used instead of sensible heat thermal energy storage (STES) an extra temperature drop would be needed. For a given solar field's outlet temperature of the heat transfer fluid, this extra temperature drop would be obtained at the expense of the maximum temperature of the ORC, that is to say, reducing its maximum temperature. This reduction in the maximum temperature of the ORC would yield a reduction in the solar cycle efficiency. A numerical example of this situation is given in Table 1 where a summary of the results obtained in POWERSOL project with respect to this issue is shown. Results correspond to operating conditions that optimize the overall efficiency of a solar ORC with R245fa as working fluid with different top temperatures (150 °C for the "cycle 2" and 230 °C for the "cycle 3") and with sensible heat and latent heat indirect thermal energy storage. Outlet and inlet solar collector temperatures were fixed at same values in both cases to make the comparison between the two configurations of the solar cycle. Melting point of the phase change material (PCM) was fixed at a lower temperature value than the inlet collector temperature (∼5 K for cycle 2 and ∼10 K for cycle 3). This value of the melting point temperature is not a specific value of any specific material. It was fixed only to make the comparison with respect to the STES configuration. As can be observed, configuration with PCM yields lower values of the efficiency of the cycle. The inclusion of the PCM in the solar organic Rankine cycle makes the ORC runs at lower evaporation and lower final superheating temperatures so the efficiency of the ORC drops. Although phase change materials could have interesting prospects as thermal storage systems they are not suitable for solar ORCs from a thermodynamic point of view because the top temperature of the ORC would be lower and this decreasing can yield an important reduction in the solar cycle efficiency.

4. Conclusions

Solar organic Rankine cycle–reverse osmosis (SORC–RO) desalination technology is one of the most promising solar desalination technologies due to the low specific energy consumption of the desalination process but also by the relatively high values of the solar to mechanical energy conversion efficiency attained with the solar ORC within the power output and hot source temperature range of application of said technology. From the analysis performed in this paper, the following design recommendations for solar desalination system based on SORC–RO can be highlighted:

Selection of the working fluid of the ORC must be assessed because many organic substances are available and the solar collector technology chosen has an influence in said selection process. Siloxane MM could be a good choice for ORC driving by parabolic trough collectors and other working substances as Solkatherm® SES36, isobutene, isopentane, R245ca and R245fa for ORC driving by stationary solar collectors.

The use of a synthetic oil as working fluid in the solar field (HTF configuration) is recommended instead of the direct evaporation of the working substance of the ORC (DVG configuration). There are no experimental results about DVG process inside the absorber tubes of parabolic trough collectors.

Analysis of the dependence of the solar ORC performance on the top temperature for a given collector is recommended. Efficiency and mass flow rates of ORC working fluid and heat transfer fluid depend on this temperature.

A carefully analysis of the top temperature of the ORC should be performed in order to make the performance of the HTF configuration as high as that of DVG configuration.

Solar collectors with linear concentrators—i.e. parabolic troughs or linear Fresnel concentrators—are recommended in order to maximise the overall efficiency of the solar desalination process. Nevertheless, if the plant location is a remote area, stationary solar collectors may be recommendable. Compound parabolic concentrators could be the best selection.

The condensation temperature of the ORC should be selected as low as possible since the use in a distillation process of the heat rejection of the solar ORC is not recommended. On the other hand, the preheating of the feedwater of the RO process may be considered.

The design of the RO subsystem should be optimized in order to minimised the solar field size. The main energy consumption

should be about 2 kWh/m^3 in an optimized design. Different membrane models of the same brand should be used in order to optimize the pressure vessel design and a careful selection of a pressure exchanger as energy recovery device should be carried out.

From a thermodynamic point of view, thermal energy storage with phase change materials is not recommended instead of sensible thermal energy storage. The ORC top temperature drop caused by the insertion of the phase change material between the solar field and the ORC unit could yield a greater reduction in the solar cycle efficiency than in the case of the sensible thermal energy storage.

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References

[1] WEO, World Energy Outlook website. http://www.iea.org/weo/database_electricity10/electricity_database_web_2010.htm; 2011 [19.04.11].
[2] WHO, World Health Organization website. http://www.wssinfo.org/data-estimates/table/; 2011 [19.04.11].
[3] Garcia-Rodriguez L. Assessment of most promising developments in solar desalination. In: Solar desalination for the 21st century. 2007. p. 355–69.
[4] Delgado-Torres AM. Solar thermal heat engines for water pumping: an update. Renew Sust Energ Rev 2009;13:462–72.
[5] Delgado-Torres AM, Garcia-Rodriguez L. Status of solar thermal-driven reverse osmosis desalination. Desalination 2007;216:242–51.
[6] Delgado-Torres AM, Garcia-Rodriguez L. Preliminary assessment of solar organic Rankine cycles for driving a desalination system. Desalination 2007;216:252–75.
[7] Delgado-Torres AM, Garcia-Rodriguez L. Comparison of solar technologies for driving a desalination system by means of an organic Rankine cycle. Desalination 2007;216:276–91.
[8] Delgado-Torres AM, Garcia-Rodriguez L, Romero-Ternero VJ. Preliminary design of a solar thermal-powered seawater reverse osmosis system. Desalination 2007;216:292–305.
[9] Delgado-Torres AM, Garcia-Rodriguez L. Double cascade organic Rankine cycle for solar-driven reverse osmosis desalination. Desalination 2007;216:306–13.
[10] Delgado-Torres AM. Diseño preliminar de un sistema de desalación por ósmosis inversa mediante energía solar térmica. PhD thesis. University of La Laguna; 2006.
[11] Garcia-Rodriguez L, Delgado-Torres AM. Solar-powered Rankine cycles for fresh water production. Desalination 2007;212:319–27.
[12] Delgado-Torres AM, García-Rodríguez L. Analysis and optimization of the low-temperature solar organic Rankine cycle (ORC). Energy Conv Manage 2010;51:2846–56.
[13] Delgado-Torres AM, García-Rodríguez L. Preliminary design of seawater and brackish water reverse osmosis desalination systems driven by low-temperature solar organic Rankine cycles (ORC). Energy Conv Manage 2010;51:2913–20.
[14] Larson DL. Performance of the Coolidge solar thermal electric power plant. J Sol Energy Eng Trans ASME 1987;109:2–8.
[15] Stine WB, Geyer M. Power cycles for electricity generation. In: Stine WB, Geyer M, editors. Power from the Sun, http://www.powerfromthesun.net/; 2011 [19.04.11].
[16] Schmidt G, Schmid P, Zewen H, Moustafa S. Development of a point focusing collector farm system. Sol Energy 1983;31:299–311.
[17] Curran HM. Use of organic working fluids in Rankine engines. J Energy 1981;5:218–23.
[18] Ghermandi A, Messalem R. Solar-driven desalination with reverse osmosis: the state of the art. Desalination Water Treat 2009;7:285–96.
[19] Wright JD. Selection of a working fluid for an organic Rankine-cycle coupled to a salt-gradient solar pond by direct-contact heat-exchange. J Sol Energy Eng Trans ASME 1982;104:286–92.
[20] Maurel A. Dessalement et energies nouvelles. Desalination 1979;31:489–99.
[21] Libert JJ, Maurel A. Desalination and renewable energies – a few recent developments. Desalination 1981;39:363–72.
[22] Manolakos D, Papadakis G, Mohamed ES, Kyritsis S, Bouzianas K. Design of an autonomous low-temperature solar Rankine cycle system for reverse osmosis desalination. Desalination 2005;183:73–80.
[23] Manolakos D, Kosmadakis G, Kyritsis S, Papadakis G. On site experimental evaluation of a low-temperature solar organic Rankine cycle system for RO desalination. Sol Energy 2009;83:646–56.
[24] Kosmadakis G, Manolakos D, Kyritsis S, Papadakis G. Simulation of an autonomous, two-stage solar organic Rankine cycle system for reverse osmosis desalination. Desalination Water Treat 2009;1:114–27.
[25] Kosmadakis G, Manolakos D, Papadakis G. Parametric theoretical study of a two-stage solar organic Rankine cycle for RO desalination. Renew Energy 2010;35:989–96.
[26] Bowman TE, El-Nashar AM, Thrasher AA, Husseiny AA, Unione AJ. Design of a small solar-powered desalination system. Desalination 1981;39:71–81.
[27] Prueitt ML. Solar energy desalination system. U.S. Patent No 6,804,962 B1. Date of Patent: Oct. 19, 2004.
[28] Karellas S, Terzis K, Manolakos D. Investigation of an autonomous hybrid solar thermal ORC-PV RO desalination system. The Chalki island case. Renew Energ 2011;36:583–90.
[29] Childs WD, Dabiri AE, Al-Hinai HA, Abdullah HA. VARI-RO solar-powered desalting technology. Desalination 1999;125:155–66.
[30] El-Nashar AM, Husseiny AA. Design aspects of a solar assisted reverse-osmosis desalting unit for urban communities. Desalination 1980;32:239–56.
[31] Husseiny AA, Hamester HL. Engineering design of a 6000 m^3/day seawater hybrid RO-ED helio-desalting plant. Desalination 1981;39:171–2.
[32] Alarcon-Padilla DC, Garcia-Rodriguez L, Blanco-Galvez J. Experimental assessment of connection of an absorption heat pump to a multi-effect distillation unit. Desalination 2010;250:500–5.
[33] Alarcón-Padilla DC, García-Rodríguez L, Blanco-Gálvez J. Design recommendations for a multi-effect distillation plant connected to a double-effect absorption heat pump: a solar desalination case study. Desalination 2010;262:11–4.
[34] Colonna P, Harinck J, Rebay S, Guardone A. Real-gas effects in organic Rankine cycle turbine nozzles. J Propul Power 2008;24:282–94.
[35] Tabor H, Bronicki L, Establishing criteria for fluids for small vapor turbines, S.A.E. Paper; 1964.
[36] E. Zarza, Generación directa de vapor con colectores solares cilindro parabólicos. Proyecto DIrect Solar Steam (DISS); 2003.
[37] Blanco J, Alarcón D, Sánchez B, Malato S, Maldonado MI, Hublitz A, Spinnler M. Technical comparison of different solar-assisted heat supply system for a multi-effect seawater distillation plant. ISES solar world congress 2003. Solar energy for a sustainable future.
[38] Peñate, B. Thermoeconimic assessment of innovations in seawater reverse osmosis plants. PhD thesis. University of Seville; 2010.